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(54) **FLUTED ADDITIVE MANUFACTURING DEPOSITION HEAD DESIGN**

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See application file for complete search history.

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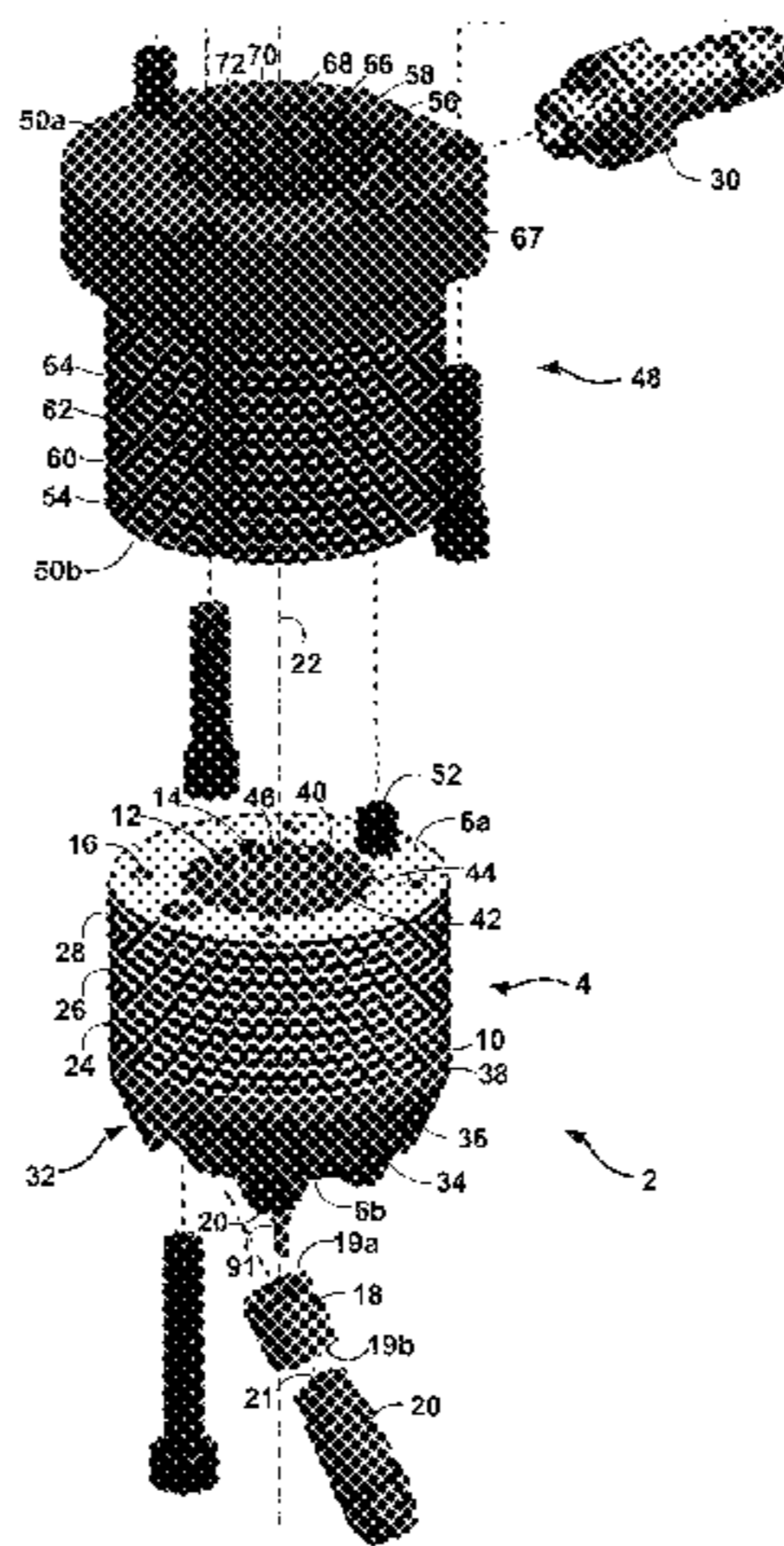
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(57) **ABSTRACT**

A material deposition head may include a body that defines first and second ends, an exterior surface, an interior surface, and one or more material delivery channels, where the exterior surface includes fluting. In some examples, a system may include a fluted material deposition head, a fluidized powder source, and an energy source.

18 Claims, 3 Drawing Sheets



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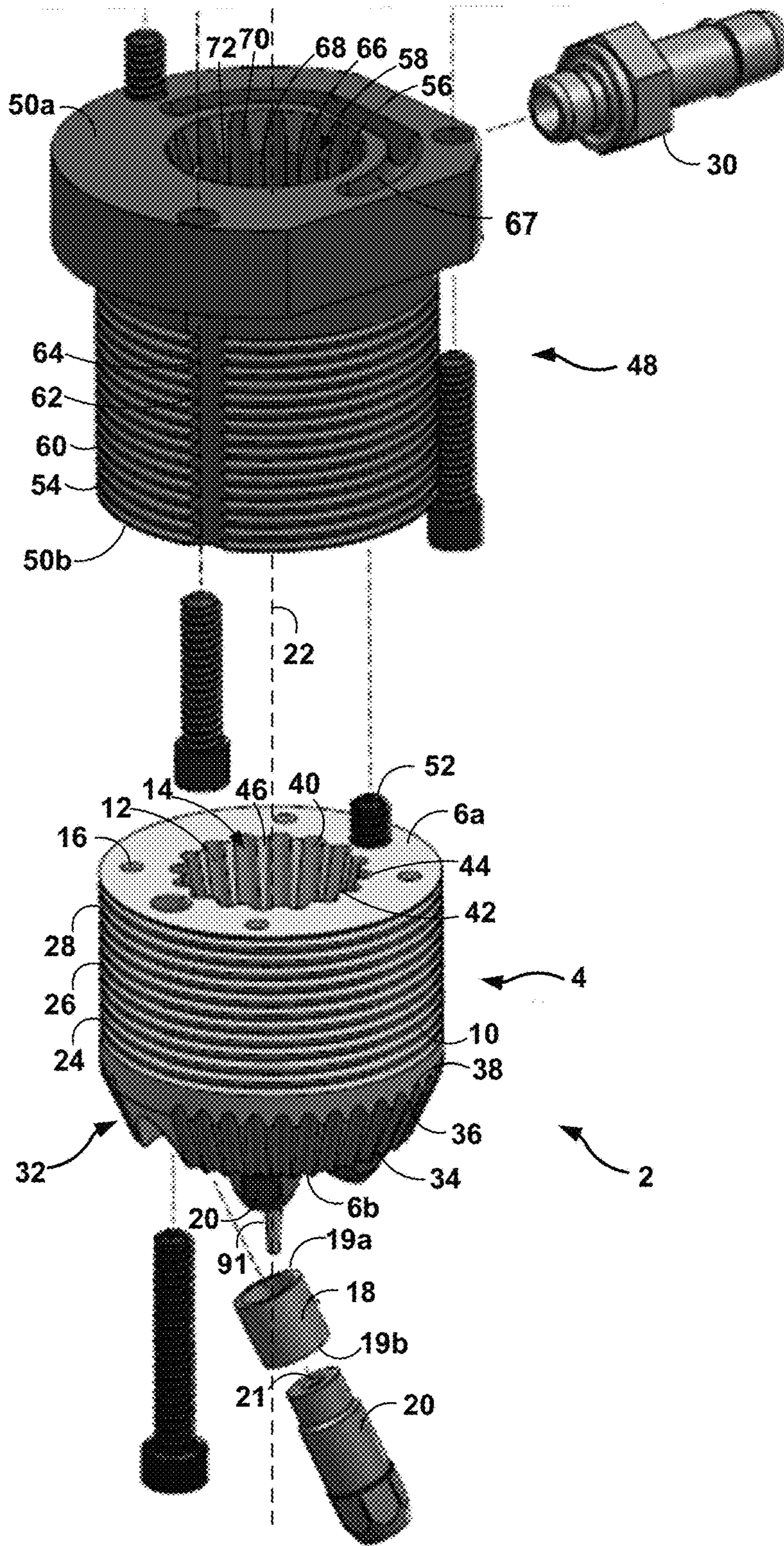


FIG. 1

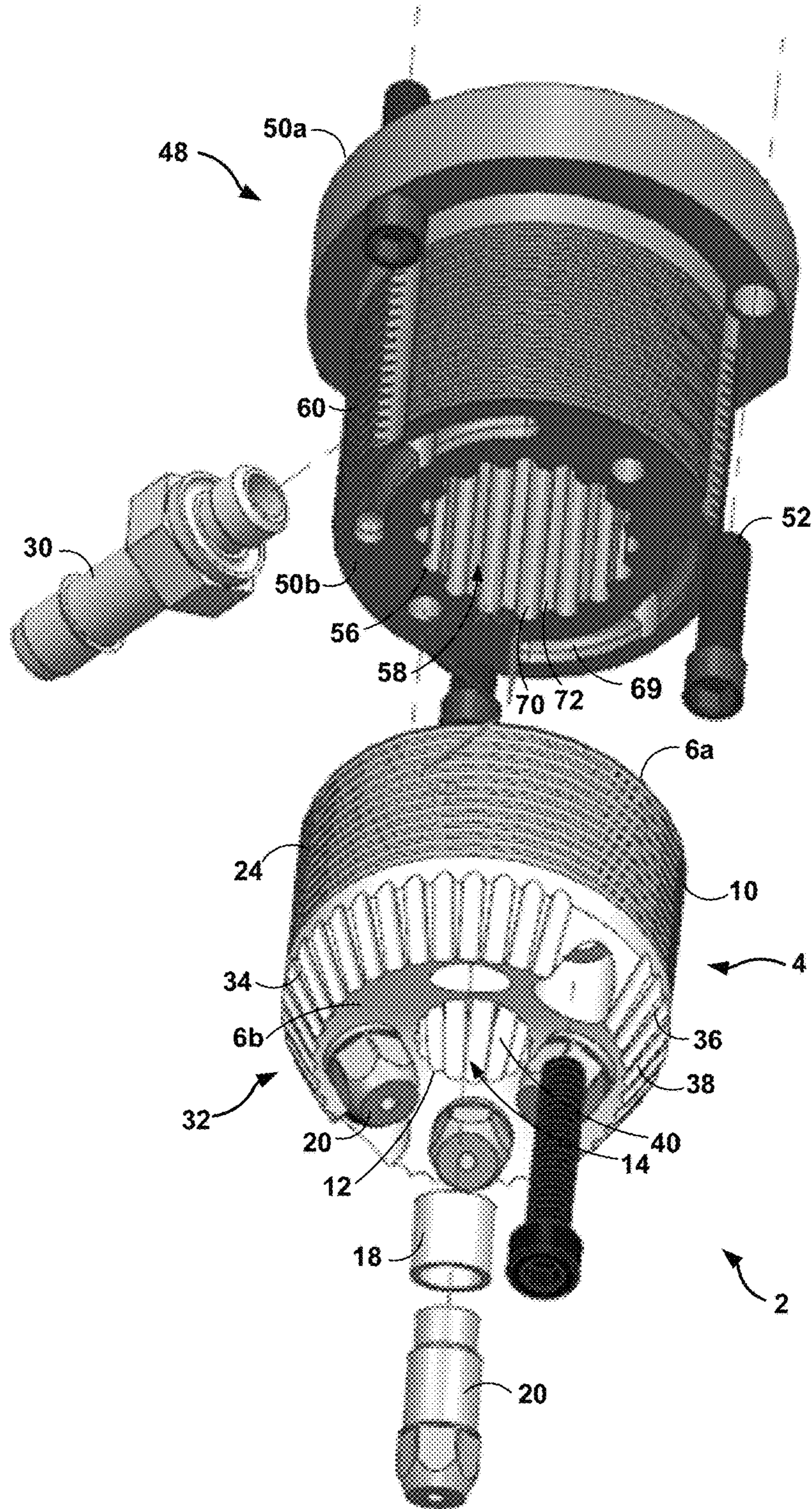


FIG. 2

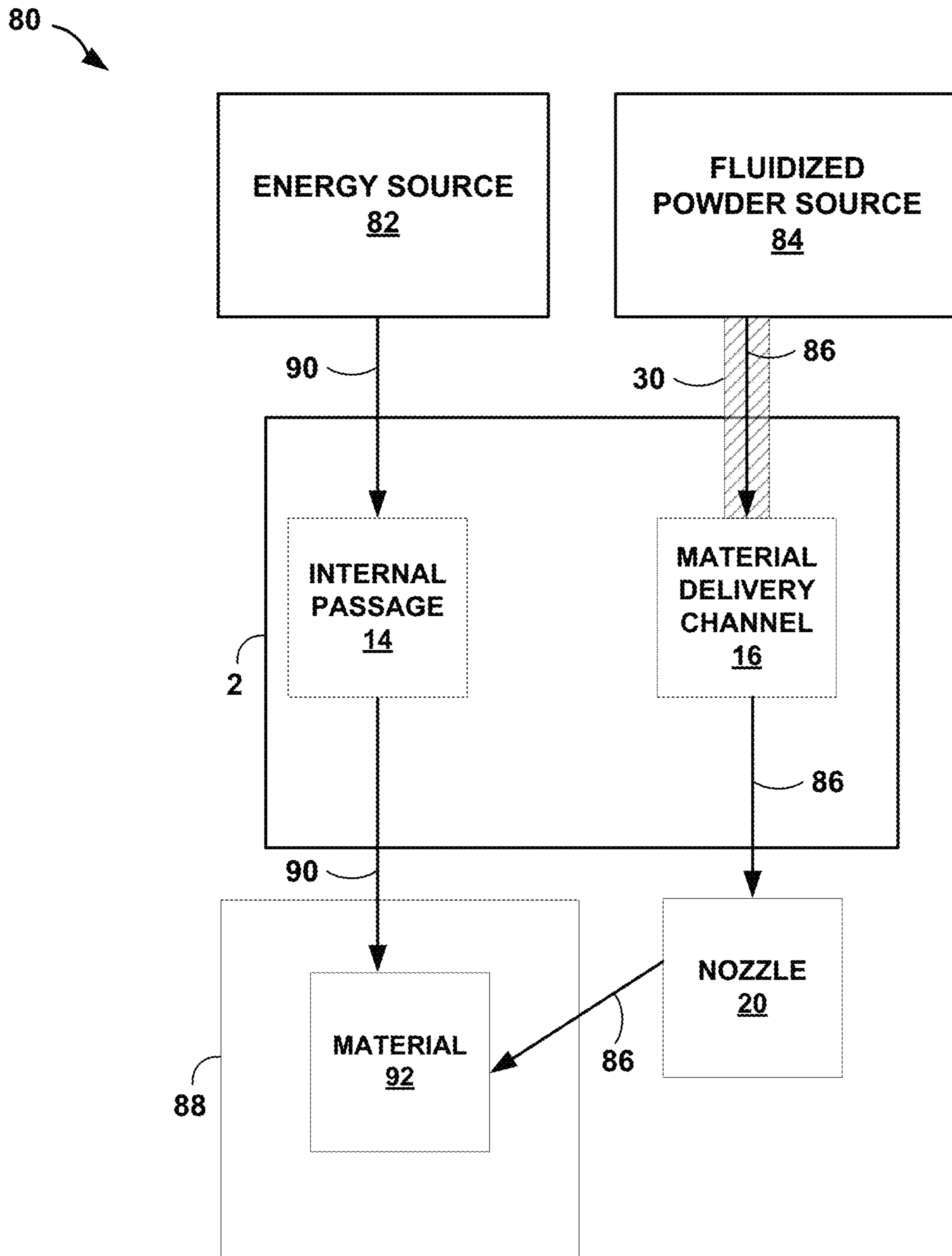


FIG. 3

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FLUTED ADDITIVE MANUFACTURING DEPOSITION HEAD DESIGN

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 62/023,442, titled, "FLUTED ADDITIVE MANUFACTURING DEPOSITION HEAD DESIGN," filed Jul. 11, 2014, the entire content of which is incorporated herein by reference.

TECHNICAL FIELD

The present disclosure describes a head for use in additive manufacturing.

BACKGROUND

Additive manufacturing generates three-dimensional structures through addition of material layer-by-layer or volume-by-volume to form the structures, rather than removing material from an existing component to generate three-dimensional structures. Additive manufacturing may be advantageous in certain circumstances, such as rapid prototyping, forming components with complex three-dimensional structures, or the like. In some examples, the additive manufacturing process may utilize a laser to melt or sinter together powdered materials in predetermined shapes to form the three-dimensional structures.

SUMMARY

The present disclosure describes a material deposition head used in the additive manufacturing process that includes fluting on one or more of its surfaces, to facilitate convection-driven cooling of and reduced absorption of heat by the head. The material deposition head may be coupled to an energy source, such as a laser. A fluid source, such as an inert gas, may carry a material through one or more internal channels of the material deposition head, which directs the material to be deposited on a substrate, to be heated by an energy source coupled to the material deposition head. For example, a laser may be positioned to deliver a laser beam through an open, inner portion of a laser material deposition head to deliver energy to and heat metal or alloy particles directed by a nozzle of the head on a substrate in a predetermined pattern. A gas that carries the metal or alloy particles through the material delivery channel of the laser material deposition head may deflect from the substrate back toward the head and pass over fluting positioned on one or more exterior surfaces of the head. Fluting may be oriented in particular directions, for example, to increase the surface area of contact between a gas and the fluting, reduce absorption of heat radiating from an energy source associated with the additive manufacturing process, or direct gas flowing over the fluting in a particular direction. Including fluting on one or more surfaces of a material deposition head may allow for higher operating temperatures or power to be used in the additive manufacturing process than otherwise would be possible without a fluted head design.

In some examples, a material deposition head of this disclosure may include a body that defines a first end and a second end, an exterior surface extending from the first end of the body to the second end of the body, and an interior surface that defines an internal passage extending from the first end to the second end. The body of the material

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deposition head also may define a material delivery channel extending from proximate to the first end of the body to proximate to the second end of the body, where the exterior surface of the body includes fluting.

In addition, in some examples, a material deposition head may be a laser material deposition head, and fluting may be disposed (e.g., by machining) on an exterior and/or interior surface of the body of the laser material deposition head. Such fluting may include a plurality of peaks connected by a plurality of troughs. An exterior surface of the body of a material deposition head of this disclosure also may include, in some examples, a chamfer that tapers inwardly toward the internal passage of the body, where the chamfer also including fluting. Additionally or alternatively, the material delivery channel of the body may include a plurality of material delivery channels, and the body may include multiple portions, for example, a first body portion and a second body portion that are configured to be coupled together.

In some examples, a system of this disclosure may include a material deposition head that has a body defining a first end and a second end, where the body further defines an exterior surface that extends from the first end of the body to the second end of the body, and an interior surface defining an internal passage that extends from the first end to the second end. Such an internal passage may be configured to permit passage of an energy beam therethrough. The material delivery channel defined by the body extends from proximate to the first end of the body to proximate to the second end of the body, wherein the material delivery channel is configured to permit passage of a fluidized powder therethrough, wherein the exterior surface of the body includes fluting. Such an exemplary system also may include a fluidized powder source coupled to the material delivery channel, and an energy source coupled to the internal passage.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is an exploded perspective view of an exemplary material deposition head described by this disclosure.

FIG. 2 is an exploded alternative view of the exemplary material deposition head of FIG. 1.

FIG. 3 is a block diagram of an exemplary system including a material deposition head, among other features, as described by this disclosure.

DETAILED DESCRIPTION

The present disclosure describes material deposition heads used in additive manufacturing (e.g., material addition or three-dimensional fabrication) that have fluting defined on one or more surfaces of the heads to at least one of facilitate cooling of the heads, reduce the absorption of heat, or enhance performance of the heads during the additive manufacturing process. During additive manufacturing, a component is built by adding material to the component in sequential layers. The final component is composed of a plurality of layers of material. In some additive manufacturing techniques for forming components from metals, alloys, polymers, or ceramics, a powder may be delivered to a surface of a previously formed layer using a carrier gas, and an energy source may be directed at predetermined volumes of the powder to heat the powder and join the

powder to the previously formed layer. The heating of the powder may, in some examples, cause the powder to sinter or melt to join the powder to the previously formed layer and/or a substrate material. The heat source may be, for example, a laser. The heat source and the sintering or melting may generate heat, at least some of which may be absorbed by the material deposition head. Left unchecked, this heating may affect operation of the material deposition head, e.g., by damaging the material deposition head.

In some examples, the material deposition head may be fluted along one or more exterior surfaces to increase convection-driven cooling of the material deposition head compared to a deposition head with no fluting, other process parameters being equal. Sources of heat that may be absorbed by the material deposition head during the additive manufacturing process may include, for example, heat from an energy beam (e.g., a laser) passing through a focal passage in the interior of the head, or heat radiating from a melt pool of material at which the laser is directed. During the additive manufacturing process, a gas carrying powdered material through a material delivery channel and out a nozzle coupled to the material deposition head may impact the substrate to which the additive manufacturing process is adding material, then deflect back toward the material deposition head. In such an example, the gas may pass over fluting on one or more exterior surfaces of the material deposition head. Fluting a surface of the material deposition head increases the total surface area of the material deposition head and may increase convection-driven cooling compared to a material deposition head without fluting on its exterior surface(s). In some examples, the fluted material deposition heads of this disclosure may exhibit an operating temperature that is about 40° C. lower than material deposition heads not including fluting, when compared under the same deposition parameters.

In some examples, the material deposition head also may be fluted along one or more interior surfaces, such as the focal passage for the energy source. For example, an inner circumference of an interior surface of the material deposition head may define a center focal passage through which an energy source, such as a laser, may be focused (e.g., focused adjacent to the surface to which material is to be added). The interior surface of the material deposition head that defines the center focal passage may be fluted.

Material deposition heads including fluting on an external surface, an internal surface, or both, may facilitate cooling of the material deposition heads without utilizing a liquid cooling medium, such as water. In some examples, water cooling of material deposition heads may be undesirable or impracticable. For example, when the size or volume of a material deposition head is small, when there is limited access to smaller components of a material deposition head, when additive manufacturing is carried out in a sealed or inert environment, and/or when reduction of the risk of water contamination is desired, water cooling of a material deposition head may be problematic. The material deposition heads described herein may reduce the risk of liquid contamination or leakage during an additive manufacturing process, may allow for a reduced footprint of the material deposition head compared to material deposition heads cooled by liquids, or both.

FIG. 1 is an exploded perspective view of an exemplary material deposition head 2 according to this disclosure. In the example illustrated in FIG. 1, material deposition head 2 includes a first body portion 4 and a second body portion 48. In other examples, material deposition head 2 may include a single body portion or more than two body portions. First

body portion 4 of material deposition head 2 defines a first end 6a and a second end 6b at opposing ends of first body portion 4, and an exterior surface 10 of body 4 extending from first end 6a to second end 6b. First body portion 4 defines a major axis 22 extending from first end 6a to second end 6b. In some examples, at least a portion of one or both of first end 6a and second end 6b includes a planar surface.

As shown in FIG. 1, first body portion 4 also may define an interior surface 12 that defines an internal passage 14 within first body portion 4. Internal passage 14 may extend from first end 6a to second end 6b of first body portion 4 and be configured to permit passage therethrough of an energy beam generated by an energy source. For example, an energy beam generated by an energy source may pass through internal passage 14 of first body portion 4, exit material deposition head 2 at second end 6b along major axis 22 (for example, in line with line 91 shown in FIG. 1), impact a material disposed on or adjacent to the substrate by a fluidized powder directed adjacent to the substrate, and be absorbed by the material. In some examples, as shown in FIG. 1, first body portion 4 may be substantially cylindrical in shape (for example, cylindrical or nearly cylindrical), such that exterior surface 10 defines an outer circumference of first body portion 4, and interior surface 12 defines an inner circumference of first body portion 4. In some such examples, first body portion 4 may be substantially annular in a radial cross-section (for example, annular or nearly annular), and the circumference of interior surface 12 is less than the circumference of exterior surface 10. The radial cross-section of first body portion 4 may be in a plane substantially orthogonal to major axis 22. First body portion 4 of material deposition head 2 may be composed of any suitable material, for example, a metal, such as aluminum or copper, an alloy, such as an aluminum alloy or a copper alloy, a ceramic, or the like. Such a material or materials may, in some examples, exhibit relatively little wear from a fluidized powder that passes therethrough.

First body portion 4 of material deposition head 2 also may define one or more material delivery channels 16 that extend from first end 6a, or from proximate to first end 6a, to second end 6b, or to proximate to second end 6b of first body portion 4. For example first, body portion 4 may define a plurality of material delivery channels 16, such as four material delivery channels 16.

In some examples, at least a portion of each channel of a plurality of material delivery channels 16 may form a separate channel then converge with other material delivery channels 16 proximate to second end 6b, in the form of a manifold or a single channel. In other examples, some or all of each channel of the plurality of delivery channels 16 may not converge proximate to second end 6b, with each channel being fluidically coupled to a respective nozzle, such as four material delivery channels 16 fluidically coupled to four respective nozzles. Material delivery channels 16 are configured to provide a path for delivery of the material to be deposited by material deposition head 2 in carrying out the additive manufacturing process. For example material deposition heads including multiple material delivery channels 16, the channels may distribute a substantially equal volume (e.g., an equal volume or nearly equal volume) of a material, such as a fluidized powder, from a material source through each of the multiple channels. In some examples, the material may be provided and flow through material delivery channels 16 as a fluidized powder, in which a flowing fluid carries powder of the material through material delivery channels 16. In some examples, the fluid includes a gas, such as, for example, a source of helium, argon, or other sub-

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stantially inert gas. As used herein, a substantially inert gas may include a gas that does not react with a substrate or the material being added to the substrate during the additive manufacturing process.

At or proximate to second end **6b** of first body portion **4** of material deposition head **2**, material delivery channels **16** may be fluidically coupled to a nozzle **20**, or each material delivery channel may be fluidically coupled to its own respective nozzle (as shown in FIG. **2**). For example, each material delivery channel of the plurality of material delivery channels **16** may be coupled to a respective nozzle **20** using an insert **18**, which may be, for example, cylindrical in shape, with an inner circumference defining an opening and an outer circumference defining an exterior surface, as shown in FIG. **1**. A first end **19a** of insert **18** (e.g., a tube or helical insert) may engage with an aperture defined in second end **6b** of first body portion **4** of material deposition head **2**, while a second end **19b** of insert **18** may be coupled to, engage with, or receive nozzle **20**. In other examples, nozzles **20** may be attached directly to first body portion **4** of material deposition head **2**, without a respective insert **18**.

Nozzle **20** includes a channel **21** that may be fluidly coupled to one or more material delivery channels **16** of first body portion **4**. Material carried by a fluid, such as a fluidized powder, may be expelled via channel **21** of nozzle **20** and directed adjacent to a surface of a substrate to be added to the surface of the substrate during the additive manufacturing process.

In some examples, first body portion **4** includes fluting **24** on exterior surface **10**. As discussed above, fluting **24** may increase the surface area of exterior surface **10** of body **4**, as compared to an exterior surface without fluting, e.g., a smooth exterior surface. Fluting **24** of exterior surface **10** of body **4** may include a plurality of peaks **26** connected by a plurality of troughs **28**, as shown in FIG. **1**. Each peak of the plurality of peaks **26** may have a width that remains constant or varies as the peak traverses exterior surface **10**, and may include a planar surface in some examples. Each trough of the plurality of troughs **28** likewise may have a width that remains constant or varies as the trough traverses exterior surface **10**. Each peak and each trough, as described, may have a same width or a different width as compared to adjacent peaks and troughs. Thus, the pitch (distance) between adjacent peaks may be constant or may vary. Moreover, the height of each peak, measured with respect to the depth of an adjacent trough, may be constant or may vary, as compared to adjacent peaks.

Fluting **24** also may include, in some examples, a series of grooves in exterior surface **10**. In some examples, at least some (or all) of the troughs of the plurality of troughs **28** of exterior surface **10** of body **4** may form a curve in axial cross-section (e.g., when fluting **24** is oriented in a direction orthogonal to major axis **22**), such as a u-shaped curve, with each end of the curve terminating at a point of a peak of the plurality of peaks **26** or at an edge of a planar surface of a peak. In other examples, the plurality of peaks **26** and plurality of troughs **28** may form a continuous curve in axial cross-section (again, when fluting **24** is oriented in a direction orthogonal to major axis **22**), such as a sinusoidal curve, as they traverse exterior surface **10**. Fluting **24** may be continuous or discontinuous in any direction (e.g., the radial or axial direction).

Additionally or alternatively, fluting **24** may be oriented in a direction substantially orthogonal (e.g., orthogonal or nearly orthogonal) to a major axis **22** of body **4** that extends from first end **6a** to second end **6b**. Orienting fluting **24** in a direction substantially orthogonal to major axis **22** of body

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4 also may place fluting **24** in a direction substantially orthogonal to the direction of flow of fluids (such as a gas) that may impact a substrate at which the material deposition head **2** is directed then deflect back toward the head **2**. In other examples, fluting **24** may be oriented in other directions, for example, oriented substantially parallel (e.g., parallel or nearly parallel) to major axis **22**, or oriented at some angle between orthogonal and parallel to major axis **22**. Fluting **24** (or any other fluting on material deposition head **2**, in general) also may allow for increased dissipation of heat (e.g., infrared energy) absorbed by body **4** or material deposition head **2** from heat sources associated with additive manufacturing, such as an energy source (e.g., a laser) or a melt pool of material being deposited. Fluting, as described by this disclosure, may be formed on first body **4** or material deposition head **2** by any suitable method, for example, by machining, material ablation, or the like. In some examples, fluting in a particular direction may be applied based, among other reasons, on ease of forming the fluting in a particular direction by use of machining.

In some examples, exterior surface **10** may include a chamfer **32** that, for example, tapers radially inwardly toward internal passage **14** proximate to second end **6b** of body **4**, as shown in FIG. **1**. A surface of chamfer **32** also may include fluting **34**. In some examples, fluting **34** may include a plurality of peaks **36** connected by a plurality of troughs **38**. In some examples, at least some (or all) of the troughs of the plurality of troughs **38** of chamfer **32** may form a curve in radial cross-section (e.g., when fluting **34** is oriented in a direction that forms an acute angle with major axis **22**), such as a u-shaped curve, with each end of the curve terminating at a point of a peak of the plurality of peaks **36** or at an edge of a planar surface of a peak. In other examples, the plurality of peaks **36** and plurality of troughs **38** on chamfer **32** may form a continuous curve in radial cross-section (again, when fluting **34** is oriented in a direction forming an acute angle with major axis **22**), such as a sinusoidal curve, as they traverse exterior surface **10**. Fluting **34** may be oriented in a direction that forms an acute angle with major axis **22**, by virtue of placement of fluting **34** on the radially inwardly tapering chamfer **32**, as shown in FIG. **1**. In other examples, fluting **34** may be oriented in other directions, for example, at some angle between orthogonal and parallel to major axis **22**.

Further, each peak of the plurality of peaks **36** may have a width that remains constant or varies as the peak traverses chamfer **32**, and may include a planar surface in some examples. For example, the planar surface of each peak of plurality of peaks **36** of chamfer **32** may narrow in width as the peak approaches second end **6b** of body **4**. Fluting **34** also may include, in some examples, a series of grooves on chamfer **32**. Fluting **34** may be continuous or discontinuous in any direction (e.g., the radial or axial direction). Each trough of the plurality of troughs **38** likewise may have a width that remains constant or varies as the trough traverses the chamfer **32**. Each peak and each trough on chamfer **32** may have a same width or a different width as compared to adjacent peaks and troughs. Thus, the pitch (distance) between adjacent peaks may be constant or vary. Moreover, the height of each peak, measured with respect to the depth of an adjacent trough, may be constant or vary, as compared to adjacent peaks.

Placement of fluting **34** on chamfer **32** in an orientation that forms an acute angle with major axis **22** may reduce absorption of heat (e.g., infrared energy) from a melt pool of material at which an energy source coupled to the material deposition head is related, increase convection driven cool-

ing of material deposition head **2** due to its increased surface area, and direct gas deflected from the substrate toward fluting **24** to facilitate convection driven cooling of material deposition head **2**. To the extent energy from an energy source (e.g., a laser) coupled to material deposition head **2** may radiate or reflect from a substrate back toward material deposition head **2** or chamfer **32**, orientation of fluting **34** on chamfer **32** in a direction that forms an acute angle with major axis **22** also may reduce absorption of energy or heat radiated or reflected from this source.

In some examples, interior surface **12** also may include fluting **40**. Fluting **40** may include a plurality of peaks **42** connected by a plurality of troughs **44**. In some examples, at least some (or all) of the troughs of the plurality of troughs **44** of interior surface **12** of body **4** may form a curve in radial cross-section (e.g., when fluting **40** is oriented in a direction parallel to major axis **22**), such as a u-shaped curve, with each end of the curve terminating at a point of a peak of the plurality of peaks **42** or at an edge of a planar surface of a peak. In other examples, the plurality of peaks **42** and plurality of troughs **44** may form a continuous curve in radial cross-section, such as a sinusoidal curve, as they traverse interior surface **12**. Fluting **40** may be continuous or discontinuous in any direction (e.g., the radial or axial direction).

In some examples, fluting **40** may be oriented in a direction that is substantially parallel to major axis **22** (for example, parallel or nearly parallel). In other examples, fluting **40** may be oriented in a direction that forms an acute angle with major axis **22**, as shown in FIG. 1. In still other examples, fluting **40** may be oriented in a direction substantially orthogonal to major axis **22**, or in any angle between orthogonal and parallel to major axis **22**. Each peak of the plurality of peaks **42** may have a width that remains constant or varies as the peak traverses interior surface **12**, and may include a planar surface **46** in some examples. For example, planar surface **46** of each peak of plurality of peaks **42** may narrow in width as the peak approaches second end **6b** of body **4**. Each trough of the plurality of troughs **44** likewise may have width that remains constant or varies as the trough traverses interior surface **12**. Each peak and each trough, as described, may have a same width or a different width as compared to adjacent peaks and troughs. Thus, the pitch (distance) between adjacent peaks may be constant or vary. Moreover, the height of each peak of the plurality of peaks **42**, measured with respect to the depth of an adjacent trough, may be constant or vary, as compared to adjacent peaks. Fluting **40** also may include, in some examples, a series of grooves in interior surface **12**.

In some examples, an inner circumference of first body portion **4** defined by interior surface **12** may decrease, and internal passage **14** of first body portion **4** may narrow, when measured in a direction moving from first end **6a** toward second end **6b**. In other examples, an inner circumference of first body portion **4** defined by interior surface **12** may stay substantially constant (e.g., constant or nearly constant), when measured in a direction moving from first end **6a** toward second end **6b**.

In some examples, a gas also may be purged through internal passage **14** of first body portion **4**, flowing from first end **6a** to second end **6b** of first body portion **4**. The gas may be sourced from, for example, a gas source coupled to material deposition head **2** coupled to material deposition head **2**. In examples that include a narrowing inner circumference of first body portion **4**, the velocity of the gas flowing through internal passage **14** may increase as the gas flows from first end **6a** to second end **6b**, increasing cooling

or heat transfer along interior fluting and/or exterior fluting when the gas deflects from the substrate back toward material deposition head **2** including exterior fluting. A gas passing through internal passage **14** with an increased velocity also may provide improved protection to optics components (e.g., an energy source, such as a laser) from splatter (e.g., metal splatter from the melt pool of material deposited on a substrate). A narrowing internal passage **14** also may prevent clipping of a converging energy beam (e.g., a laser beam) that passes through internal passage **14**. In some examples, a narrowing internal passage **14** may create additional space at second end **6b** of first body portion **4** for placement of additional components, such as for one or more nozzles coupled to second end **6b** of first body portion **4**. Further, placement of fluting **40** on interior surface **12** in an orientation that forms an acute angle with major axis **22** may reduce absorption of heat from a melt pool of material at which an energy source coupled to the material deposition head is related, increase convection driven cooling of material deposition head **2** due to its increased surface area, and direct gas deflected from the substrate toward fluting **24** for additional convection-driven cooling of the head.

As illustrated in FIG. 1, in some examples, material deposition head **2** may include a first body portion **4** configured to be coupled to a second body portion **48**. Second body portion **48** may define a first end **50a** and a second end **50b** at opposing ends of second body portion **48**. In some examples, at least a portion of one or both of first end **50a** and second end **50b** includes a planar surface. Second body portion **48** also defines major axis **22** extending from first end **50a** to second end **50b**. In such an example, first body portion **4** and second body portion **48** may be coupled by any suitable means, such as by one or more of a plurality of screws **52** that pass through at least part of first body portion **4** and at least part of second body portion **48**, as shown in FIG. 1. For example, first end **6a** of first body portion **4** may be coupled to second end **50b** of second body portion **48** by a plurality of screws **52** disposed in respective threaded holes of a plurality of threaded holes in first body portion **4** and second body portion **48** that are aligned. First body portion **4** or second body portion **48** also may include holes, threaded holes, or any other suitable means that allows either of first body portion **4** or second body portion **48** to be attached to the other portion or to other components associated with the additive manufacturing system. In general, material deposition head **2**, or certain portions thereof, may include machined regions that enable components of the head **2** to be mechanically fastened together, or the head **2** to be mechanically fastened to other components used in the additive manufacturing system.

As shown in FIG. 1, second body portion **48** may include an exterior surface **54** that extends from first end **50a** to second end **50b**. Second body portion **48** also may define an interior surface **56** that defines an internal passage **58** within second body portion **48**. Internal passage **58** may extend from first end **50a** to second end **50b** of second body portion **48**. When first body portion **4** and second body portion **48** are assembled, internal passage **58** of second body portion **48** may be substantially aligned (e.g., aligned or nearly aligned) with internal passage **14** of first body portion **4**, such that the internal passages together may be configured to allow passage of an energy beam therethrough during the additive manufacturing process. In some examples, as shown in FIG. 1, second body portion **48** may be substantially cylindrical in shape (e.g., cylindrical or nearly cylindrical), such that exterior surface **54** defines an outer circumference of second body portion **48**, and interior surface

56 defines an inner circumference of second body portion **48**. In some such examples, second body portion **48** may be substantially annular in a radial cross-section (e.g., annular or nearly annular), and the circumference of interior surface **56** is less than the circumference of exterior surface **54**. The radial cross-section of second body portion **48** may be in a plane substantially orthogonal to major axis **22**. Second body portion **48** of material deposition head **2** may be composed of any suitable material, for example, a metal, such as aluminum or copper, an alloy, such as an aluminum alloy or copper alloy, a ceramic, or the like.

Second body portion **48** of material deposition head **2** also may define one or more material delivery channels (not shown in FIG. **1**) that extend from first end **50a**, or from proximate to first end **50a**, to second end **50b**, or to proximate to second end **50b** of second body portion **48**. For example, second body portion **48** may define a plurality of material delivery channels, such as four channels. In some examples, each material delivery channel of the plurality of material delivery channels of the second body portion **48** may be substantially aligned (e.g., aligned or nearly aligned) with and/or fluidically coupled to a respective material delivery channel of material delivery channels **16** of first body portion **4**, such that the channels are configured to provide a path for delivery of the material (e.g., a fluidized powder) to be deposited by material deposition head **2** in carrying out the additive manufacturing process. In other such examples, each material delivery channel of the plurality of delivery channels **16** of first body portion **4** may be fluidically coupled to at least one material delivery channel of second body portion **48**. For example, two material delivery channels **16** of first body portion **4** may be fluidically coupled to one material delivery channel of second body portion **48**, and two other material delivery channels **16** of first body portion **4** may be fluidically coupled to one other material delivery channel of second body portion **48** of material deposition head **2**. As noted, in some example material deposition heads, first body portion **4** may have a different number of material delivery channels **16** than second body portion **48**. For example, an introductory channel **67** (as shown in FIG. **1**) on the surface of first end **50a** may be fluidically coupled to two material delivery channels that extend from first end **50a** to second end **50b** of second body portion **48**. In such an example, each delivery channel of second body portion **48** may be fluidically coupled to a respective transitional channel **69** in the surface of second end **50b** (shown in FIG. **2**), where each transitional channel **69** is fluidically coupled to one or more material delivery channels **16** of first body portion **4** (e.g., each transitional channel **69** may be fluidically coupled to two material delivery channels **16** of first body portion **4**).

At or proximate to first end **50a** of second body portion **48** (as shown in FIG. **1**), material delivery channels (not shown in FIG. **1**) of second body portion **48** may be coupled with tube **30**, which fluidically connects the material delivery channels to a fluidized powder source, or in some examples, a fluid source (e.g., a gas source) or a material source (e.g., a powder source). In some examples, as shown in FIG. **1**, tube **30** may be fluidically coupled to the material delivery channels of second body portion **48** via introductory channel **67**. Although FIG. **1** illustrates a single tube **30** for fluidically coupling material delivery channels of second body portion **48** to a fluidized powder source, in other examples, material deposition head **2** may include a plurality of tubes **30** for fluidically coupling material delivery channels of second body portion **48** to one or more gas, material, or fluidized powder sources. A gas, material, or fluidized powder source

also may be fluidically coupled to material deposition head **2** using a tube, pipe, conduit, or the like, that allows fluid communication. As described, the material the fluid carries, to be deposited in a layer on a substrate, may include at least one of a metal, alloy (e.g., an alloy of nickel and titanium), ceramic, or polymer. In some examples, such as when material deposition head **2** includes a single body portion, tube **30** may fluidically couple a fluidized powder source to material delivery channels **16** of first body portion **4**.

In some examples, second body portion **48** includes fluting **60** on exterior surface **54**. As discussed above, fluting **60** may increase the surface area of exterior surface **54** of second body portion **48**, as compared to an exterior surface without fluting, e.g., a smooth exterior surface. Similar to exterior surface **10** of first body portion **4**, fluting **60** of exterior surface **54** of second body portion **48** may include a plurality of peaks **62** connected by a plurality of troughs **64**, as shown in FIG. **1**. Each peak of the plurality of peaks **62** may have a width that remains constant or varies as the peak traverses exterior surface **54**, and may include one or more planar surfaces in some examples. Each trough of the plurality of troughs **64** likewise may have a width that remains constant or varies as the peak traverses exterior surface **54**. Each peak and each trough, as described, may have a same width or a different width as compared to adjacent peaks and troughs. Thus, the pitch (distance) between adjacent peaks may be constant or vary. Moreover, the height of each peak, measured with respect to the depth of an adjacent trough, may be constant or may vary, as compared to adjacent peaks.

Fluting **60** also may include, in some examples, a series of grooves in exterior surface **54**. In some examples, at least some (or all) of the troughs of the plurality of troughs **64** of exterior surface **54** of second body **48** may form a curve in axial cross-section (e.g., when fluting **60** is oriented in a direction orthogonal to major axis **22**), such as a u-shaped curve, with each end of the curve terminating at a point of a peak of the plurality of peaks **62** or at an edge of a planar surface of a peak. In other examples, the plurality of peaks **62** and plurality of troughs **64** may form a continuous curve in axial cross-section (again, when fluting **60** is oriented in a direction orthogonal to major axis **22**), such as a sinusoidal curve, as they traverse exterior surface **54**. Fluting **60** may be continuous or discontinuous in any direction (e.g., the radial or axial direction). For example, fluting **60** may be disposed continuously on the entirety of exterior surface **54**, or disposed only on portions of exterior surface **54**.

Additionally or alternatively, fluting **60** may be oriented in a direction substantially orthogonal (e.g., orthogonal or nearly orthogonal) to the major axis **22** of second body portion **48** that extends from first end **50a** to second end **50b**. Orienting fluting **60** in a direction substantially orthogonal to major axis **22** of second body portion **48** also may place fluting **60** in a direction substantially orthogonal to the direction of flow of fluids (such as a gas) that may impact a substrate at which the material deposition head **2** is directed then deflect back toward the head **2**. In other examples, fluting **60** may be oriented in other directions, for example, oriented substantially parallel (e.g., parallel or nearly parallel) to major axis **22**, or oriented at some angle between orthogonal and parallel to major axis **22**. In some examples, fluting **60** on exterior surface **54** of second body portion **48** may be oriented in a different direction than fluting **24** on exterior surface **10** of first body portion **4**. In other examples, fluting **60** and fluting **24** are oriented in the same direction with respect to major axis **22**. Fluting **60** may allow for increased dissipation of heat (e.g., infrared energy) absorbed by second body portion **4** or material deposition head **2** from

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heat sources associated with additive manufacturing, such as an energy source (e.g., a laser) or a melt pool of material being deposited.

In some examples, interior surface **56** of second body portion **48** also may include fluting **66**. Fluting **66** may include a plurality of peaks **68** connected by a plurality of troughs **70**. Each peak of the plurality of peaks **68** may have a width that remains constant or varies as the peak traverses interior surface **56**, and may include one or more planar surfaces **72** in some examples. For example, planar surface **72** of each peak of plurality of peaks **68** may narrow in width as the peak approaches second end **50b** of second body portion **48**. In some examples, each trough of the plurality of troughs **70** likewise may have a width that remains constant or varies as the trough traverses interior surface **56**. In some examples, one or more parts of some peaks of the plurality of peaks **68** may include a curvilinear surface.

Each peak and each trough, as described, may have a same width or a different width as compared to adjacent peaks and troughs. Thus, the pitch (distance) between adjacent peaks may be constant or vary. Moreover, the height of each peak, measured with respect to the depth of an adjacent trough, may be constant or vary, as compared to adjacent peaks.

Fluting **66** also may include, in some examples, a series of grooves in interior surface **56**. In some examples, at least some (or all) of the troughs of the plurality of troughs **70** of interior surface **56** may form a curve in radial cross-section (e.g., when fluting **66** is oriented in a direction parallel to major axis **22**), such as a u-shaped curve, with each end of the curve terminating at a point of a peak of the plurality of peaks **68** or an edge of a planar surface of a peak. In other examples, the plurality of peaks **68** and plurality of troughs **70** may form a continuous curve in radial cross-section, such as a sinusoidal curve, as they traverse interior surface **56**. Fluting **66** may be continuous or discontinuous in any direction (e.g., the radial or axial direction).

In some examples, fluting **66** may be oriented in a direction that is substantially parallel to major axis **22** (for example, parallel or nearly parallel), as shown in FIG. 1. In other examples, fluting **66** may be oriented in a direction that is substantially orthogonal to major axis **22**. In still other examples, fluting **66** may be oriented in a direction that forms some angle with major axis **22** between orthogonal and parallel to major axis **22**.

In some examples, an inner circumference of second body portion **48** defined by interior surface **56** may decrease, and internal passage **58** of second body portion **48** may narrow, when measured in a direction moving toward second end **50b**. For example, placement of fluting **60** on interior surface **56** in a parallel orientation or an orientation that forms an acute angle with major axis **22** may reduce absorption of heat from an energy source (e.g., a laser or energy beam), from a melt pool of material at which an energy source coupled to material deposition head **2** is related, and increase convection driven cooling of material deposition head **2** due to its increased surface area.

FIG. 2 is an exploded alternative view of the example material deposition head **2** shown in FIG. 1. FIG. 2 illustrates, for example, two transitional channels **69**, each transitional channel **69** being formed in a surface of second end **50b** of second body portion **48**. Each transitional channel **69** is fluidically coupled to one or more material delivery channels of second body portion **48** (e.g., each transitional channel **69** is fluidically coupled to one material delivery channel of second body portion **48**) and to one or more material delivery channels **16** of first body portion **4** (e.g.,

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each transitional channel **69** is fluidically coupled to two material delivery channels **16** of first body portion **4**). FIG. 2 also illustrates second end **6b** of first body portion **4** including a concave surface to which one or more nozzles **20** (e.g., four nozzles) are coupled. In some examples, second end **6b** may include a substantially planar surface (e.g., planar or nearly planar). FIG. 2 also shows that the inner circumference of first body portion **4** defined by interior surface **12** may decrease, and internal passage **14** of first body portion **4** may narrow, when measured in a direction moving from first end **6a** toward second end **6b**. As shown in FIG. 2, a narrowing internal passage **14** may create additional space at second end **6b** for placement of additional components, such as for one or more nozzles **20** coupled to second end **6b** of first body portion **4**.

FIG. 3 is a conceptual block diagram of an example system **80** described by this disclosure, which may include a material deposition head **2**. Material deposition head **2** of system **80** may include some or all of the various features described herein with respect to material deposition head **2** and FIG. 1. Similar to or the same as described with respect to exemplary material deposition head **2** of FIG. 1, material deposition head **2** of system **80** may include a single body or multiple bodies (e.g., first body portion **4** and second body portion **48**), and may include fluting on an external surface and, optionally, an interior surface.

The body of material deposition head **2** also may define one or more material delivery channels **16** that extend from proximate to the first end of the body to proximate to the second end of the body. The one or more material delivery channels **16** of the body of material deposition head **2** may be configured to permit passage of a fluidized powder **86** therethrough. Fluidized powder **86** may be supplied by a fluidized powder source **84** coupled to material delivery channels **16** of the body of material deposition head **2** of system **80**. Fluidized powder **86** may include, for example, metal, alloy, ceramic, or polymeric particles carried by a gas. Fluidized powder source **84** may include, for example, a source of helium, argon, or other substantially inert gas fluidically coupled with a source of powder, such as metal, alloy, ceramic, or polymeric particles. Fluidized powder source **84** may be subject to, for example, pressure or vacuum, to enable delivery of fluidized powder **86** from fluidized powder source **84** through a tube (such as tube **30**), material delivery channels **16**, and a channel of a nozzle (e.g., channel **21** of nozzle **20**, as described with reference to FIG. 1).

System **80** also may include an energy source **82** coupled to (e.g., mechanically coupled to, or positioned in alignment with) an internal passage **14** defined by the body of material deposition head **2**. Energy source **82** may generate an energy beam **90** that passes through internal passage **14** and heats a material **92** disposed on a substrate **88** by the fluidized powder **86** directed at substrate **88** via nozzle **20**, as shown in FIG. 3. Material **92** may include, for example, metal, alloy, ceramic, or polymeric particles, e.g., metal, alloy, ceramic, or polymeric particles from fluidized powder **86**. In some examples, energy source **82** may include a laser, plasma source, plasma arc, electrical arc, ultraviolet energy source, infrared energy source, induction coil, or another source of energy may be coupled to (e.g., mechanically coupled to) a material deposition head. Example laser sources include a CO laser, a CO₂ laser, a Nd:YAG laser, or the like. For example, system **80** may include a laser positioned to direct a laser beam generated by the laser through the internal passage defined by the body of a laser material deposition head, such that the laser beam heats

metal, alloy, ceramic, or polymeric particles directed at a substrate as part of the additive manufacturing process. In some examples, energy source **82** may be selected to provide energy beam **90** with a predetermined wavelength or wave-length spectrum that may be absorbed by material **92** to be added to substrate **88** during the additive manufacturing process. A laser may operate during the additive manufacturing process to heat, sinter, or melt the material being added to the substrate (or being joined to the substrate) at temperatures in the range of 1000° C. to 4000° C. with respect to materials such as polymers, including copolymers, thermoplastics, and thermosets; ceramics, including carbides, nitrides, and oxides; metals, alloys (e.g., nickel-base alloys and titanium-based alloys), ferrous metallic alloys, or non-ferrous metallic alloys. In additive manufacturing processes that utilize lasers operating in the referenced temperature range but do not include material deposition heads including the fluting described by this disclosure, such deposition heads may warm to at least 300° C. during the additive manufacturing process, which may cause distortion to components of the head (e.g., metal components, such as aluminum alloy components).

Nozzle **20** coupled to material deposition head **2**, as described with respect to FIGS. **1** and **2**, or material deposition head **2** itself, may be positioned at any number of angles with respect to substrate **88**. In some examples, nozzle **20** and/or material deposition head **2** may be movable in at least one dimension (e.g., translatable and/or rotatable) to direct fluidized powder **86**, and/or energy beam **90** from energy source **82** toward a selected location adjacent to a substrate. For example, the direction of the path of fluidized powder **86** expelled through nozzle **20** may form an acute angle or right angle with substrate **20**. Additionally or alternatively, substrate **88** may be movable in at least one dimension relative to material deposition head **2** so that material deposition head **2**, and/or components thereof, interact with a selected location adjacent to substrate **88**.

In some examples, the material deposition head described herein is an ultra small diameter material deposition head, for example, a cylindrically shaped material deposition head that has a diameter of less than half an inch. The material deposition head may be used in material deposition techniques for additive manufacturing of relatively small components or adding material to locations of components with relatively small clearances. Because of the small size of the material deposition head, using water cooling may not be practical, as the water cooling components may make the material deposition head too large to fit in the desired spaces. Thus, the fluting provided on surfaces of the material deposition head described herein may provide increased cooling of the material deposition head compared to a material deposition head without fluting, while reducing or minimizing an increase in size of the material deposition head.

Clause 1: A material deposition head comprising: a body defining a first end and a second end, wherein the body further defines: an exterior surface extending from the first end of the body to the second end of the body; an interior surface defining an internal passage extending from the first end to the second end; and a material delivery channel extending from proximate to the first end of the body to proximate to the second end of the body, wherein the exterior surface of the body includes fluting.

Clause 2: The material deposition head of clause 1, wherein the material deposition head comprises a material deposition head coupled to an energy source.

Clause 3: The material deposition head of clause 1 or 2, wherein the fluting of the exterior surface of the body comprises a plurality of peaks connected by a plurality of troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the body that extends from the first end to the second end.

Clause 4: The material deposition head of any one of clauses 1-3, wherein the interior surface of the body comprises fluting comprising a plurality of peaks connected by a plurality of troughs, and wherein at least a portion of the fluting of the interior surface is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

Clause 5: The material deposition head of any one of clauses 1-4, wherein the exterior surface of the body includes a chamfer that tapers radially inwardly toward the internal passage proximate to the second end of the body, wherein a surface of the chamfer comprises fluting comprising a plurality of peaks connected by a plurality of troughs, and wherein the fluting of the chamfer is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

Clause 6: The material deposition head of any one of clauses 1-5, wherein the material delivery channel comprises a plurality of material delivery channels.

Clause 7: The material deposition head of any one of clauses 1-6, wherein the body is substantially cylindrical and substantially annular in a radial cross-section, the circumference of the interior surface being less than the circumference of the exterior surface.

Clause 8: The material deposition head of any one of clauses 1-7, wherein the body comprises a first body portion, and the material deposition head further comprises a second body portion defining a first end and a second end, the second end of the second body portion being configured to be coupled to the first end of the first body portion, wherein the second body portion further defines: an exterior surface extending from the first end of the second body portion to the second end of the second body portion; an interior surface defining an internal passage extending from the first end to the second end, wherein the internal passage of the second body portion is substantially aligned with the internal passage of the first body portion; and a material delivery channel extending from proximate to the first end of the second body portion to proximate to the second end of the second body portion, wherein the material delivery channel of the second body portion is fluidically coupled to the material delivery channel of the first body portion, and wherein the exterior surface of the second body portion includes fluting.

Clause 9: The material deposition head of clause 8, wherein the fluting of the exterior surface of the second body portion comprises a plurality of peaks connected by a plurality of troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the second body portion that extends from the first end to the second end of the second body portion.

Clause 10: The material deposition head of clause 8 or 9, wherein the interior surface of the second body portion comprises fluting comprising a plurality of peaks connected by a plurality of troughs, and wherein at least a portion of the fluting of the interior surface of the second body is oriented in a direction substantially parallel to a major axis of the second body portion that extends from the first end to the second end of the second body portion.

Clause 11: The material deposition head of any one of clauses 8-10, wherein the material delivery channel of the

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first body portion comprises a plurality of material delivery channels, and the material delivery channel of the second body portion comprises a plurality of material delivery channels, wherein each respective material delivery channel of the plurality of material delivery channels of the first body portion is fluidically coupled to at least one material delivery channel of the plurality of material delivery channels of the second body portion.

Clause 12: The material deposition head of any one of clauses 8-11, wherein the second body portion is substantially cylindrical and substantially annular in a radial cross-section, the circumference of the interior surface being less than the circumference of the exterior surface of the second body portion.

Clause 13: A system comprising: a material deposition head comprising a body defining a first end and a second end, wherein the body further defines: an exterior surface extending from the first end of the body to the second end of the body; an interior surface defining an internal passage extending from the first end to the second end, wherein the internal passage is configured to permit passage of an energy beam therethrough; and a material delivery channel extending from proximate to the first end of the body to proximate to the second end of the body, wherein the material delivery channel is configured to permit passage of a fluidized powder therethrough, and wherein the exterior surface of the body includes fluting; a fluidized powder source coupled to the material delivery channel; and an energy source coupled to the internal passage.

Clause 14: The system of clause 13, wherein the material deposition head comprises a laser material deposition head, the fluidized powder comprises at least one of metal, alloy, ceramic, or polymeric particles carried by a fluid, the energy source comprises a laser, and the energy beam comprises a laser beam generated by the laser.

Clause 15: The system of clause 13 or 14, wherein the fluting of the exterior surface of the body comprises a plurality of peaks connected by a plurality of troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the body that extends from the first end to the second end.

Clause 16: The system of any one of clauses 13-15, wherein the interior surface of the body comprises fluting comprising a plurality of peaks connected by a plurality of troughs, wherein at least a portion of the fluting of the interior surface is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

Clause 17: The system of any one of clauses 13-16, wherein the exterior surface of the body includes a chamfer that tapers radially inwardly toward the internal passage proximate to the second end of the body.

Clause 18: The system of clause 17, wherein a surface of the chamfer comprises fluting comprising a plurality of peaks connected by a plurality of troughs, wherein the fluting of the chamfer is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

Clause 19: The system of any one of clauses 13-18, wherein the body comprises a first body portion, and the material deposition head further comprises a second body portion defining a first end and a second end, the second end of the second body portion being configured to be coupled to the first end of the first body portion, wherein the second body portion further defines: an exterior surface extending from the first end of the second body portion to the second end of the second body portion; an interior surface defining

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an internal passage extending from the first end to the second end, wherein the internal passage of the second body portion is substantially aligned with the internal passage of the first body portion; and a material delivery channel extending from proximate to the first end of the second body portion to proximate to the second end of the second body portion, wherein the material delivery channel of the second body portion is fluidically coupled to the material delivery channel of the first body portion, wherein the exterior surface of the second body portion includes fluting.

Clause 20: The system of clause 19, further comprising: a tube configured to be coupled to the material delivery channel defined by the second body portion proximate to the first end of the second body portion, wherein the tube is configured to transport fluidized powder from the fluidized powder source; a nozzle configured to be coupled to the second end of the first body portion, wherein the nozzle is fluidically coupled to the material delivery channel of the first body portion and configured to deliver the fluidized powder adjacent to a substrate.

Various examples have been described. These and other examples are within the scope of the following claims.

The invention claimed is:

1. A material deposition head comprising:

a body defining a first end and a second end, wherein the body further defines:

an exterior surface, at least a portion of the exterior surface of the material deposition head extending from the first end of the body to the second end of the body;

an interior surface defining an internal passage extending from the first end to the second end; and

a material delivery channel extending from proximate to the first end of the body to proximate to the second end of the body, wherein the material delivery channel is configured to permit passage of a fluidized powder therethrough, wherein the at least portion of the exterior surface includes fluting configured to increase a surface area of the exterior surface of the body and increase convection-driven cooling of the material deposition head, wherein the fluting of the exterior surface comprises a plurality of peaks connected by a plurality of troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the body that extends from the first end to the second end, and wherein at least some troughs of the plurality of troughs of the at least a portion of the exterior surface of the body form a curve in axial cross-section with each end of the curve terminating at a point of a peak of the plurality of peaks or at an edge of a planar surface of the peak.

2. The material deposition head of claim 1, wherein the material deposition head is configured to be coupled to an energy source.

3. The material deposition head of claim 1, wherein the interior surface of the body comprises fluting comprising a plurality of peaks connected by a plurality of troughs, and wherein at least a portion of the fluting of the interior surface is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

4. The material deposition head of claim 1, wherein the exterior surface includes a chamfer that tapers radially inwardly toward the internal passage proximate to the second end of the body, wherein a surface of the chamfer comprises fluting comprising a plurality of peaks connected

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by a plurality of troughs, and wherein the fluting of the chamfer is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

5 5. The material deposition head of claim 1, wherein the material delivery channel comprises a plurality of material delivery channels.

6. The material deposition head of claim 1, wherein the body is substantially cylindrical and substantially annular in a radial cross-section, a circumference of the interior surface 10 being less than a circumference of the exterior surface.

7. The material deposition head of claim 1, wherein the body comprises a first body portion, and the material deposition head further comprises a second body portion defining a first end and a second end, the second end of the second 15 body portion being configured to be coupled to the first end of the first body portion, wherein the portion of the exterior surface comprises a first portion, and wherein the second body portion further defines: 20

at least a second portion of an exterior surface of the material deposition head extending from the first end of the second body portion to the second end of the second body portion;

25 an interior surface of the second body portion defining an internal passage extending from the first end to the second end, wherein the internal passage of the second body portion is substantially aligned with the internal passage of the first body portion; and

30 a material delivery channel for the second body portion extending from proximate to the first end of the second body portion to proximate to the second end of the second body portion, wherein the material delivery channel of the second body portion is fluidically coupled to the material delivery channel of the first 35 body portion, and wherein the second portion of the exterior surface includes fluting.

8. The material deposition head of claim 7, wherein the fluting of the exterior surface of the second portion comprises a plurality of peaks connected by a plurality of 40 troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the second body portion that extends from the first end to the second end of the second body portion.

9. The material deposition head of claim 7, wherein the interior surface of the second body portion comprises fluting 45 comprising a plurality of peaks connected by a plurality of troughs, and wherein at least a portion of the fluting of the interior surface of the second body is oriented in a direction substantially parallel to a major axis of the second body 50 portion that extends from the first end to the second end of the second body portion.

10. The material deposition head of claim 7, wherein the material delivery channel of the first body portion comprises a plurality of material delivery channels, and the material 55 delivery channel of the second body portion comprises a plurality of material delivery channels, wherein each respective material delivery channel of the plurality of material delivery channels of the first body portion is fluidically coupled to at least one material delivery channel of the 60 plurality of material delivery channels of the second body portion.

11. The material deposition head of claim 7, wherein the second body portion is substantially cylindrical and substantially annular in a radial cross-section, a circumference of the interior surface being less than a circumference of the 65 exterior surface of the second body portion.

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12. A system comprising:

a material deposition head comprising a body defining a first end and a second end, wherein the body further defines:

an exterior surface, at least a portion of an exterior surface of the material deposition head extending from the first end of the body to the second end of the body;

an interior surface defining an internal passage extending from the first end to the second end, wherein the internal passage is configured to permit passage of an energy beam therethrough;

a material delivery channel extending from proximate to the first end of the body to proximate to the second end of the body, wherein the material delivery channel is configured to permit passage of a fluidized powder therethrough, wherein the at least a portion of the exterior surface includes fluting configured to increase a surface area of the exterior surface of the body and increase convection-driven cooling of the material deposition head, wherein the fluting of the exterior surface comprises a plurality of peaks connected by a plurality of troughs, wherein the plurality of peaks are oriented in a direction substantially orthogonal to a major axis of the body that extends from the first end to the second end, and wherein at least some troughs of the plurality of troughs of the at least a portion of the exterior surface of the body form a curve in axial cross-section with each end of the curve terminating at a point of a peak of the plurality of peaks or at an edge of a planar surface of the peak;

a fluidized powder source coupled to the material delivery channel; and

an energy source coupled to the internal passage.

13. The system of claim 12, wherein the material deposition head comprises a laser material deposition head, the fluidized powder comprises at least one of metal, alloy, ceramic, or polymeric particles carried by a fluid, the energy source comprises a laser, and the energy beam comprises a laser beam generated by the laser.

14. The system of claim 12, wherein the interior surface of the body comprises fluting comprising a plurality of peaks connected by a plurality of troughs, wherein at least a portion of the fluting of the interior surface is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

15. The system of claim 12, wherein the exterior surface includes a chamfer that tapers radially inwardly toward the internal passage proximate to the second end of the body.

16. The system of claim 15, wherein a surface of the chamfer comprises fluting comprising a plurality of peaks connected by a plurality of troughs, wherein the fluting of the chamfer is oriented in a direction that forms an acute angle with a major axis of the body that extends from the first end to the second end.

17. The system of claim 12, wherein the body comprises a first body portion, and the material deposition head further comprises a second body portion defining a first end and a second end, the second end of the second body portion being configured to be coupled to the first end of the first body portion, wherein the portion of the exterior surface comprises a first portion, and wherein the second body portion further defines:

at least a second portion of an exterior surface of the material deposition head extending from the first end of the second body portion to the second end of the second body portion;

an interior surface of the second body portion defining an internal passage extending from the first end to the second end, wherein the internal passage of the second body portion is substantially aligned with the internal passage of the first body portion; and 5

a material delivery channel for the second body portion extending from proximate to the first end of the second body portion to proximate to the second end of the second body portion, wherein the material delivery channel of the second body portion is fluidically 10 coupled to the material delivery channel of the first body portion, wherein the second portion of the exterior surface includes fluting.

18. The system of claim 17, further comprising: 15

a tube configured to be coupled to the material delivery channel defined by the second body portion proximate to the first end of the second body portion, wherein the tube is configured to transport fluidized powder from the fluidized powder source; 20

a nozzle configured to be coupled to the second end of the first body portion, wherein the nozzle is fluidically coupled to the material delivery channel of the first body portion and configured to deliver the fluidized powder adjacent to a substrate. 25

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